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14. ABSTRACT
The focus of the project is to develop control theoretic models with supporting decision making methods to address the problem of strategic decision making for military operations in an environment that is strongly influenced by the presence of interacting subcultures. The specific directions of the project are: 1) Modeling of social behaviors that address incomplete information and indeterminate models for uncertainty management, 2) Robust decision-making based on incentive design, optimization, and learning, and 3) Constructive computational tools.

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Final Report

Control Theoretic Modeling for Uncertain Cultural Attitudes and Unknown Adversarial Intent

Grant #FA9550–05–1–0239

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Objectives

The focus of the project is to develop control theoretic models with supporting decision making methods to address the problem of strategic decision making for military operations in an environment that is strongly influenced by the presence of interacting subcultures. The specific directions of the project are: 1) Modeling of social behaviors that address incomplete information and indeterminate models for uncertainty management, 2) Robust decision-making based on incentive design, optimization, and learning, and 3) Constructive computational tools.

Research Directions

The research effort was focused on four areas, 1) *forecasting enemy intent:* the development of constructive forecasting algorithms that provide statistically consistent forecasts in the absence of underlying process models; 2) *dynamic adaptation in coordination games:* the analysis of learning rules based on overreactionary behaviors; 3) *analysis of rational social learning in networks:* analysis of belief propagation in social networks in various network topologies; and 4) *distributed multi-agent optimization:* analysis and development of distributed optimization methods in multi-agent networks that operate with local information and computations.

Accomplishments

Forecasting enemy intent: The problem is to develop a statistically consistent forecast of a recurring event. Prior work derived "universal" forecasting algorithms that guaranteed statistical consistency regardless of the underlying process generating the recurring event. A severe drawback of these algorithms is that they are essentially impossible to implement. Our work has developed a forecasting algorithm that trades off computationally feasibility with universality. The forecasting method provides statistically consistent forecasts for a large class of opponent models while having very modest computational requirements.

Our work also broadened the scope to forecasting performance of competing policies in unknown reactionary environments. We have developed an algorithm that adaptively switches between alternate policies in an effort to determine which is most effective. The forecasting method assures that the resulting performance asymptotically approaches that of the best policy.

This work has been accepted for journal publication, conference publication, and presentation.

Dynamic adaptation in coordination games: Our work has shown that "dynamic adaptation" can enable qualitative changes of behavior when compared to more conventional learning models. In this work, we investigate dynamic adaptation for coordination. A simple example is as follows. There are two competing conventions, A and B. A group of agents is in equilibrium when all follow either convention A or convention B. However, convention A is more efficient in that all agents would achieve a greater reward. In conventional distributed reinforcement learning, convention B becomes a stable attractor. In our "dynamic adaptation" version of reinforcement learning, actions are reinforced by *both* rewards and rate of change of rewards. The result is that efficient convention A becomes the only stable attractor — even if only one agent uses dynamic adaptation.

Follow on work has focused on specializing the general methodology as a predictive device for social network formation and for communication network formation with constraints on the lengths of communication chains.

This work has been presented as a conference publication and is under preparation for journal submission.

Analysis of rational social learning in networks: In social networks, an important issue is to understand the propagation of information through the network, i.e., individuals learning from others' actions and information made available through other channels (such as media). In the context of communities of social networks, much of the learning comes in the form of word-of-mouth or communication between neighbors and acquaintances. This phenomenon is sometimes referred to as social learning.

Although there is a large literature in economics on social learning, this literature does not focus on the implications of the social network topology and interaction structure on the information dissemination and belief formation. Most of the work relies on the unrealistic assumption of perfect observability of the entire history of actions. Our interest in this work is to determine how outcomes of social learning is sensitive to observation structures, social network topology, or deliberate manipulation.

In recent work, we presented an analysis of social learning on a line network when individuals have access to a "noisy" measurement of a fixed unknown variable and only observe the action of their immediate neighbor. The resulting structure is the so-called Bayes-Nash equilibrium. Despite the simplicity of this environment, the evolution of beliefs is substantially different from the typical models of social learning in the game theory literature. We characterized the behavior of asymptotic learning in terms of threshold values that evolve deterministically. Individual actions are fully determined by the value of their signal relative to these thresholds. We characterized conditions on the private information of the individuals under which they can learn the true value of the variable. In more recent work, we extended our analysis to general network topologies and developed conditions on the network topology that lead to "asymptotic learning". We also presented rate of convergence results that highlight the dependence on the observation window length.

This work has been accepted for conference publication and presentation, and two journal publications are being prepared for submission.

Distributed Multi-Agent Optimization: We consider a cooperative multi-agent environment, where each agent has a local cost function and constraint structure, which is known to that agent only. We introduce a new framework for the development and analysis of distributed asynchronous optimization algorithms to optimize the global objective of the sum of the individual local cost functions. For this purpose, we use *first-order* or *subgradient methods* which are gaining popularity in the optimization community as low-overhead alternatives to interior point methods for large-scale convex optimization that lend themselves to distributed implementations. We consider a distributed computation model, whereby every agent generates and maintains estimates of the optimal solution, and communicates them directly or indirectly to the other agents, potentially with delays. Each agent updates their estimate by combining it with the estimates received from the others agents (if any) and by using the gradient (or subgradient) information of the local cost function. In recent work, we have established convergence results and convergence rate estimates for this model. Our results are novel in the sense that they capture the tradeoffs associated with the suboptimality of the solutions and the computational complexity of the algorithms.

This work has been presented in conferences and has appeared as journal publications.

We have also pursued game theoretic approaches to distributed multi-agent optimization. Most work in learning in games assumes that the same conflict/game is infinitely repeated. In stochastic games, the conflict depends on an underlying state, and the state evolution depends on the actions taken by the players in the game. We have investigated the special case where the "state" is the immediately preceding action of an agent, i.e., the set of possible actions at one stage is constrained by the action taken in the previous stage. We have derived learning algorithms with guaranteed convergence properties for special classes of multiagent games with this state dependency. We also have investigated the issue of agent information. Much work on learning assumes agents can measure the actions taken by other agents. We have investigated the more natural assumption where agents only measure their own realized reward and need not have a closed form expression of their own utility functions. We have established convergence results for certain

classes of games under such constraints.

This work has been accepted for journal publication, conference publication, and presentation.

Personnel Supported by and/or Associated with Project

Faculty:

- Jeff S. Shamma, UCLA & Georgia Institute of Technology
- Munther A. Dahleh, MIT
- Asuman Ozdaglar, MIT

Students:

- George Chasparis, UCLA
- Jason Marden, UCLA
- Ibrahim Al-Shyoukh, UCLA
- Ilan Lobel, MIT

Publications Submitted and/or Accepted

- S. Mannor, J.S. Shamma, and G. Arslan, "Online calibrated forecasts: Memory efficiency vs universality for learning in games", *Machine Learning*, Special issue on "Learning and Computational Game Theory", May 2007, pp. 77 - 115.
- J.R. Marden, G. Arslan, and J.S. Shamma, "Connections between cooperative control and potential games illustrated on the consensus problem", *2007 European Control Conference*, Kos, Greece.
- G. Chasparis and J.S. Shamma, "Distributed dynamic reinforcement of efficient outcomes in multiagent coordination", *2007 European Control Conference*, Kos, Greece.
- D. Acemoglu, M. Dahleh, I. Lobel and A. Ozdaglar, "Bayesian Learning in Social Networks", LIDS Working Paper #2780, 2008, submitted for journal publication.
- D. Acemoglu and A. Ozdaglar, "Competition in Parallel-Serial Networks," selected for fast-track to *IEEE Journal on Selected Areas in Communications*, special issue on Non-cooperative Behavior in Networking, vol. 25, no. 6, pp. 1180–1192, August 2007.
- D. Acemoglu, R. Johari, and A. Ozdaglar, "Partially Optimal Routing, *IEEE Journal on Selected Areas in Communications*, special issue on Non-cooperative Behavior in Networking, vol. 25, no. 6, pp. 1148–1160, August 2007.
- A. Ozdaglar and R. Srikant, "Pricing and Incentives in Communication Networks", chapter in *Algorithmic Game Theory*, Noam Nisan, Tim Roughgarden, Eva Tardos, and Vijay Vazirani, editors, Cambridge University Press, 2007.
- J.R. Marden, H.P. Young, G. Arslan, and J.S. Shamma, "Payoff based dynamics for multiplayer weakly acyclic games",

- *SIAM Journal on Control and Optimization*, special issue on "Control and Optimization in Cooperative Networks", to appear 2009.
- *46th IEEE Conference on Decision and Control*, New Orleans, Louisiana, 2007.

- I.A. Al-Shyoukh and J.S. Shamma, "Switching Supervisory Control Using Calibrated Forecasts",
  - *46th Conference on Decision and Control*, New Orleans, LA, December, 2007.
  - *IEEE Transactions on Automatic Control*, to appear 2009.
- I.A. Al-Shyoukh, *Online-information-based learning and decision making under uncertainty*, Ph.D. Dissertation, UCLA, June 2007.
- J.R. Marden, *Learning in Large-Scale Games and Cooperative Control*, PhD Dissertation, UCLA, June, 2007.
- I. Lobel, D. Acemoglu, M. Dahleh, and A. Ozdaglar, "Social Learning with Partial Observations,"
  - *46th Conference on Decision and Control*, New Orleans, LA, December, 2007.
  - *Workshop on interdisciplinary systems approach in performance evaluation and design of computer and communication systems*, France, 2007.
- A. Nedić and A. Ozdaglar, "Distributed Subgradient Methods for Multi-agent Optimization,"
  - *46th Conference on Decision and Control*, New Orleans, LA, December, 2007.
  - *IEEE Transactions on Automatic Control*, January 2009, pp. 48–61.
- A. Ozdaglar, "Constrained Consensus and Alternating Projections," *45th Annual Allerton Conference on Communication, Control, and Computing*, 2007, invited paper and presentation.
- G. Chasparis and J.S. Shamma, "Efficient network formation by distributed reinforcement", accepted for publication, *47th IEEE Conference on Decision and Control*, 2008.
- G. Chasparis, "Distributed Learning and Efficient Outcomes in Uncertain and Dynamic Environments," PhD Dissertation, University of California, Los Angeles, Department of Mechanical & Aerospace Engineering, Los Angeles, CA, May 2008.

Interactions/Transitions

- Participation/presentations at meetings, conferences, seminars, etc.
  - "Learning in games and feedback control", presented at the *Caltech Workshop on Integrated Control, Estimation and Communication*, Pasadena, CA, March 31–April 2, 2005.
  - "Calibrated forecasts: Efficiency versus universality", presented at the *The 16th International Conference on Game Theory at Stony Brook University*, Stony Brook, NY, July 11–15, 2005.
  - J.S. Shamma, "Control theoretic methods for competition and evolution", *Caltech Workshop on Learning and Information in Games and Control* , Pasadena, CA, March 22–23, 2006.
  - J.S. Shamma, "Learning in Games and Feedback Control", *Economic Theory Workshop*, University of Wisconsin, September 15, 2006.

- A. Ozdaglar, "Economic Incentives and Traffic Engineering in Networked-Systems," MIT Information Technology Conference on "Next Generation Computing and Wireless Networks", April 2006.
- A. Ozdaglar, "Competition and Efficiency in Congested Networks", Radcliffe Exploratory Seminar on Dynamic Networks: Behavior, Optimization and Design, Radcliffe Institute, Harvard University, October 21–22, 2006.
- J.R. Marden, H.P. Young, G. Arslan, and J.S. Shamma, "Convergence Results for Payoff-Based Dynamics in Weakly Acyclic Games", presented at *18th Annual International Conference on Game Theory*, Stony Brook, NY, July 9–13, 2007.
- G. Chasparis, G. and J.S. Shamma, "Distributed Dynamic Reinforcement of Efficient Outcomes in Multiagent Coordination, presented at *European Control Conference*, Greece, Kos, July 2–5, 2007.
- J.R. Marden, G. Arslan and J.S. Shamma, "Connections Between Cooperative Control and Potential Games Illustrated on the Consensus Problem", presented at *Proceedings of the 2007 European Control Conference*, Kos, Greece, July, 2007.
- G. Chasparis and J.S. Shamma, "The Emergence of Efficient Social Networks by Dynamic Reinforcement," presented at *4th Lake Arrowhead Conference on Human Complex Systems*, April 25–29, 2007.
- G. Chasparis, "Dynamic Reinforcement of Efficient Outcomes in Multi-Agent Coordination", Social and Information Sciences Laboratory, California Institute of Technology, June 2007.
- I. Lobel, "Social Learning with Partial Observations," presented at *18th Annual International Conference on Game Theory*, Stony Brook, NY, July 9–13, 2007.
- A. Ozdaglar, "Price and Capacity Competition," presented at the *The Economics of the Software and Internet Industries Conference*, Toulouse; January 2007.
- A. Ozdaglar, "Distributed Multi-agent Optimization," presented at the *22nd European Conference on Operational Research: Nonsmooth Optimization, Theory, Algorithms, and Applications*, Prague; July 2007.
- Asuman Ozdaglar & Jeff S. Shamma presented works at the Caltech Microeconomic Dynamics Workshop, May 2008.
- Asuman Ozdaglar & Jeff S. Shamma were co-organizers of the Workshop on Frontiers of Game Theory and Networked Control Systems, October 2008.
- Jeff S. Shamma presented at the AFOSR Workshop on Mathematical Modeling of Socio-Cultural Processes, Santa Barbara, CA, September 2008.
- Jeff S. Shamma presented the Jones Seminar on Science, Technology, and Society, Dartmouth College, May 2008.

- Consultative and advisory functions to other laboratories and agencies.
  - Munther A. Dahleh: Sandia National Labs
  - Jeff S. Shamma: Air Force Scientific Advisory Board.
- Transitions: None to report.

New discoveries, inventions, or patent disclosures

None to report.

Honors/Awards

- Munther Dahleh:
  - IEEE Fellow.
- Asuman Ozdaglar:
  - NSF CAREER Award.
  - MIT Class of '43 Career Development Chair, May 2006.
  - American Automatic Control Council Donald P. Eckman Award, 2008.
- Jeff Shamma:
  - IEEE Fellow.
  - Julian T. Hightower Chair in Systems and Control, Georgia Institute of Technology.
- Jason Marden:
  - Outstanding graduating mechanical engineering PhD student, UCLA, 2007.